

**DEVELOPMENT OF SKID TESTING
IN INDIANA**

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**Joint
Highway
Research
Project**

by
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DEVELOPMENT OF SKID TESTING IN INDIANA

TO: K. B. Woods, Director
Joint Highway Research Project

March 13, 1956

FROM: Harold L. Michael, Assistant Director

File: 9-3-4-1
C-36-530

Attached is a paper entitled, "Development of Skid Testing in Indiana." This paper has been prepared by Harold L. Michael and D. L. Grunau of our staff. It was presented at the annual meeting of the Highway Research Board in Washington, D.C. on January 18, 1956.

This paper reports the development of equipment and the results of skid tests on various surfaces in the state. The equipment used has received considerable attention by individuals and organizations in all parts of the United States and a great deal of interest has developed in its construction.

It is anticipated that this paper will be published by the Highway Research Board.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Assistant Director
Joint Highway Research Project

HLM:ejg

Attachment

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by

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Joint Highway Research Project

File: 9-3-4-1

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Purdue University
Lafayette, Indiana

March 13, 1956

DEVELOPMENT OF SKID TESTING IN INDIANA

ABSTRACT

Many studies have been made in recent years with various types of skid equipment to evaluate skidding characteristics of pavement surfaces. This paper briefly summarizes in 2011 with funding from the results found in these studies and presents a detailed description of a skid-resistant braking device used on a conventional automobile in Indiana.

The device is electrically operated and when activated applies the brakes and initiates measurement of stopping distance simultaneously. The speed at which the brakes were activated is also recorded. The method used eliminates much of the human variable from the measurement of stopping distance and makes it possible for the good reproduction of stopping distance.

The skid testing program in Indiana is also outlined and preliminary results are presented. A number of experimental surfaces were tested along with four major surface types used in Indiana. These four were: Rock Asphalt, Portland Cement Concrete, Bituminous Concrete, and

other Bituminous Surfaces. A total of 233 different roads were tested; each road being tested at three locations with two skids being performed at each location.

The skidding properties of the various roads were compared in terms of mean skid distances at 30 mph. Variability of the skid distances was determined along with the means.

The tests showed that Rock Asphalt had the best skidding properties of all the surfaces tested with respect to both average distance and variability. Its mean skid distance changed little between the wet and dry condition. Portland Cement Concrete surfaces provided relatively good skid characteristics but were subject to some polishing by traffic during the first few years of their life. The Bituminous Concrete surfaces tested had poorer skid characteristics than any other major type considered. The Bituminous Surfaces tested, other than Rock Asphalt and Bituminous Concrete, had a relatively low mean but were extremely variable. This variability was almost invariably associated with bleeding. Those roads with no bleeding yielded a mean 18 feet less than those that displayed some bleeding. The bituminous roads constructed with limestone aggregate had a lower mean than those containing gravel, although the limestone in some cases polished extensively under prolonged heavy traffic.

INTRODUCTION

In 1954, drivers in the United States became involved in 30,800 fatal and 1,276,700 non-fatal accidents. Many of these accidents were primarily the fault of the drivers involved, but a great number might have been minimized or prevented by safer highways. Although many factors are involved in the building of safety into highways, one of the more important items is the resistance of pavement surfaces to skidding, especially when these surfaces are wet. Seventeen percent of the fatal and nineteen percent of the non-fatal accidents in 1954 occurred on wet pavements. When consideration is given to the fact that pavements are wet for less than nineteen percent of the time, and travel is usually reduced during wet periods, it is evident that a disproportionate number of accidents occur under these conditions. How many accidents could be avoided by better skidding characteristics is unknown; but as many accidents involve some type of skidding, the number is undoubtedly of considerable magnitude.

In Indiana, it is generally recognized that certain types of pavements have better skidding characteristics than others, but few measurements have ever been taken on a comparative basis. Experimental sections have been constructed in the past few years, and several new surface types are being used. Some of these surfaces are quite economical and durable, but little is known of their skidding properties. If the new surfaces are dangerously slippery the reduced construction cost is of extremely dubious value, unless they can be redesigned so as to make them satisfactory

Only a few investigators have conducted an extensive program of research to determine the relative characteristics of pavements. Possibly the most complete data have been obtained by Professor R. A. Meyer, formerly of the State College and currently at the University of California in Berkeley. In his earliest tests, as reported in 1933, a two-wheel trailer towed by a motor truck was used. The trailer was constructed so it could be used to measure impending skid, straight-locked-wheel skid, and slide skid. The skidding force was measured by integrating a dynamometer linkage to the towing truck. The wheels were locked or braked with Bendix self-energizing mechanical brakes which were manually operated. Two to four runs were made in each direction, wet and dry, at 3, 5, 10, 20, 30, and 40 mph, and the dynamometer force was averaged over a distance of from 50 to 150 feet.

One of the first detailed reports on another method of test, the automobile stopping-distance method, resulted from work conducted in Virginia by T. E. Shelburne and R. L. Sheppe, reported in 1948. Here a standard, light-weight automobile was used with manually operated brakes. The skid distance was measured by taping the distance from a chalk mark fired from a device mounted on the running board. The roads were compared by computing the coefficients of friction at speeds of 10, 20, 30, and 40 miles per hour. The coefficient of friction was computed by the standard formula $F = \frac{V^2}{30S}$, where F equals the average coefficient of friction, V equals the initial speed in miles per hour at the time of applying brakes, and S equals the average stopping distance in feet. This formula has been used for almost all subsequent tests that have employed the stopping distance method.

Other methods of test, such as a motorcycle sidecar used in England and a trailer with pivoted wheels used in France, have been reported and numerous conclusions from these skid studies have presented valuable information on skid characteristics. Much remains to be done in this area, however, and in order to obtain estimates of the skid characteristics of Indiana road surfaces and to investigate some of the factors that affect skid resistance a long-range study was undertaken.

Research on skid-resistance was initiated by the Joint Highway Research Project in November, 1950. At that time Mr. John F. McLaughlin presented a "Report and Annotated Bibliography on Skid Resistance." In 1951 field observations of driver reaction and reliability of test equipment were made. From June 1952 to the summer of 1953, further tests, using the automobile-stopping distance method, were conducted by Mr. John Paerwald. The primary purpose of these tests was to develop testing procedures and to provide data for comparison of the skid resistance qualities of pavement surfaces. From these preliminary tests a formal field study was determined to be advisable.

DEVELOPMENT OF A PROGRAM

Testing Device

A preliminary study was conducted in order to determine the testing method that would be the most satisfactory and that would be safe and economical. The vehicle-stopping-distance method was determined to be the best for this study even though the towed-trailer method was found to have some advantages. The latter method is certain to give very accurate results as it uses sensitive instruments and results are averaged over a considerable length of pavement. Tests can be run fast and safely as the unit is self contained and does not require that traffic be stopped. The towed-trailer method, however, has definite disadvantages. It is expensive to build; there is a possibility of differences in skidding characteristics between a towed object and a freely skidding unit; and there is some doubt that the "hot spot" developed underneath one wheel of a towed trailer as it is dragged over a long distance will give performance characteristics similar to those obtained from four locked wheels skidding over a shorter distance. Finally, several investigators have indicated that there is a difference between the skidding resistance of a pavement in the initially wet stage and of one in a flushed condition. This presents a possibility that wetting a surface at high speed immediately before a skidding wheel might give unrealistic results.

Because of these considerations, the Joint Highway Research Project adopted the basic concept of using the stopping distance of a freely skidding vehicle to compare skidding properties of pavements. In its original form this method of test enabled use of a standard 1951 Ford equipped with a chalk-marking device mounted on the rear bumper.

the wiring being attached to the brake pedal by a large clamp connected in series with a simple pull-apart connector. To run a test the driver would connect the proper wiring and load the chalk marker with a chalk cartridge. He would then bring the vehicle to a speed slightly in excess of the test speed, disengage the clutch, let the vehicle coast to the proper speed and slam on the brake, bringing the car to a skidding stop. The movement of the brake pedal fired the chalk marker, and the distance from the mark to the final position of the car was taped.

It was felt at the outset of this survey that this method in its initial form was too crude and presented several disadvantages. Some of these were:

1. The driver may differ in his reaction time from skid to skid and day to day.
2. The driver may differ in his brake-pedal pressure from skid to skid.
3. The driver may miss the test speed by a considerable amount.
4. The "pull-apart" connector for the chalk marker did not release at the same instant for each brake application. This error would not necessarily be corrected by connecting the marker to the brake-light system as this system has large variations in "tripping" pressure.
5. The considerable time required to measure each skid with a tape created serious traffic problems and evaporation

often made it impossible to run more than one skid at a site on hot days without rewetting. Wetting a surface before each skid would impose a problem in the procurement of sufficient water and require much more testing time.

It was thus decided to modify the test car to minimize or eliminate these disadvantages. The idea evolved to outfit the car with some type of electrically operated power brake that would give a constant braking pressure with each application. This could be connected with an accurate fifth-wheel speedometer-odometer that would automatically close the braking circuit at a pre-determined test speed and then measure the distance required to stop.

Letters explaining the problem were sent to many major concerns dealing with the manufacture of power brakes and speedometers. It soon became apparent that a speedometer that would close a circuit at a pre-determined speed would be difficult to construct, and the necessary centrifugal switch would have a rather wide range of closing values. An alternative electrical speedometer could do the job accurately, but proved too expensive and would not measure distance. It was therefore decided to close the brake circuit manually and to find an instrument that would record the speed as the brakes were applied. The "Wagner Stopmeter" manufactured by the Wagner Electric Company of St. Louis, Missouri, fulfilled this requirement and was available at a reasonable cost. A unit was subsequently purchased.

A study of possible braking systems revealed that a vacuum brake system would be the most practical and economical for test purposes. Air pressure and electrical brakes were investigated but the cost of adapting either of these systems would have been far greater

than that for the vacuum system. The Bendix Products Division of the Bendix Aviation Corporation of South Bend, Indiana, proposed a very simple, electrically-operated, vacuum-braking unit. This unit was eventually constructed and installed in the test car by the Bendix Corporation.

The Bendix System is illustrated in Figure 1. The heart of the system is the vacuum unit that operates a Ford master cylinder (E) through a simple lever system (F). The vacuum chamber (A) is activated when an electrical impulse opens the solenoid valve (D) which, in turn, opens the vacuum valve (C).

The vacuum thus created in the left side of the vacuum chamber causes atmospheric pressure to force the lever system (F) to the left, thus activating the master cylinder (E). The vacuum is supplied by the intake manifold of the engine through a line (J). A one-way valve (I) was installed to eliminate any losses in the vacuum reserve tank (B) during periods of low manifold vacuum. A brake fluid reservoir (H) was included with lines running to master cylinder (E) and to the car master cylinder, so as to eliminate the possibility of pumping fluid between the car system and the power system.

Line pressure applied by master cylinder (E) causes the shuttle valve (G) to close the line to the standard car master cylinder and allows line pressure to be distributed to the individual wheels for braking. When the current to the solenoid valve (D) is discontinued the pressure is instantly relieved and application of the standard car brake will transfer the shuttle valve (G) for all normal operation of the brakes. The diameter of the shuttle valve was reduced from 1/2" to 1/4" to eliminate the possibility of a large amount of fluid displacement when the valve is shifted. This modification was made to the original design.

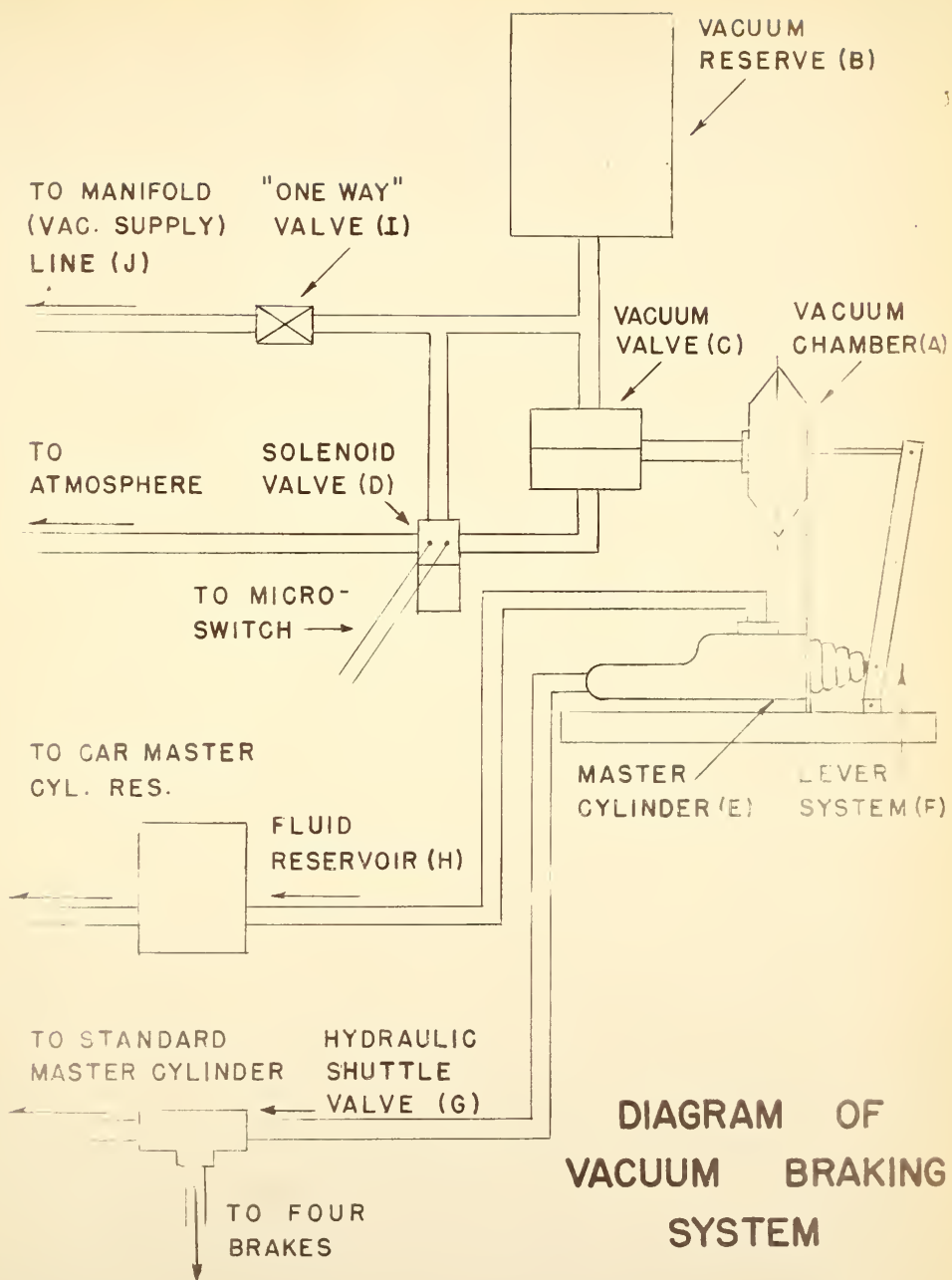


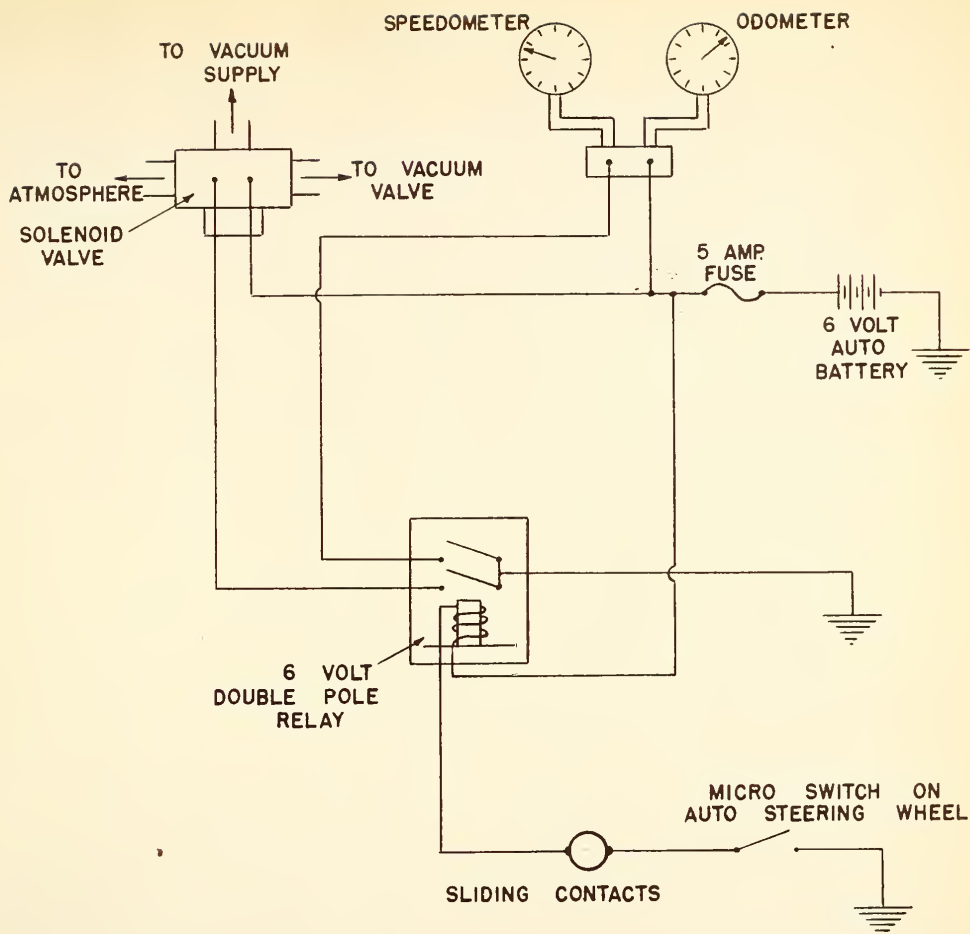
FIGURE NO. I

the normal method. The system, as outlined, was installed in the trunk of the test car by Bendix personnel and operated without incident through the entire series of tests. The power system applies a brake line pressure of approximately $700\#/in^2$ and locks the wheels in less than 0.17 of a second.

With the braking problem solved, there remained a need for a method which would permit the driver to conveniently lock the brakes and activate the Wagner Stopmeter at the desired speed. After consideration of several types of foot switches, it was apparent that more positive and sensitive driver control could be realized by a hand-operated switch. A micro-switch was mounted on the steering wheel rim and connected to a circular copper contact plate at the wheel base. A carbon brush was set in the steering column so that it was in contact with the circular plate for all positions of the steering wheel and was connected into the coil of a 6-volt double-pole relay. The relay was connected as shown in the wiring diagram (Figure 3) to the solenoid valve and the odometer and speedometer.

These modifications made skid testing quite simple and minimized the driver variable. In order to make a test run the driver merely has to let the car slow down to the test speed as indicated by the special speedometer and press the micro-switch. This action locks the brakes and at the same instant it holds the speedometer and activates the odometer. At the end of the skid it is possible to record the braking speed and the skid distance from the stopmeter dials. This testing method has proven to be extremely consistent.

The preliminary tests indicated a problem with the brake-backing plates. The manufacturer, however, supplied the project with special reinforced plates and no further difficulty of this type was encountered.



WIRING DIAGRAM
OF
BRAKING CIRCUIT

Method of Testing

Each selected road is tested in at least 3 locations, with 2 skids performed at each location. A location is a level, straight stretch of pavement 200 to 300 feet in length and located anywhere on the road. It is usually possible to select the locations in such a manner as to allow adequate sight distances for flagmen to stop traffic safely.

Most skids are run at 30 mph. The primary reason that one speed was chosen was that the interest is in comparing the skid resistance of the various road surfaces and not in studying the effects of various speeds. The selection of one speed also allows more roads to be tested in the available time. Thirty mph. was selected as it was considered to be the highest speed that could safely be used over the wide range of road types that exist in Indiana. The fact that the test car left the road many times during the testing to date indicates that a greater speed would be quite hazardous.

The purpose of these tests is to investigate the skidding properties of roads and since the wet condition is the most critical, almost all of the tests are run under wet conditions. The only equipment necessary is the test vehicle, a water truck, two red flags, two thermometers, data sheets, clipboard and pencil. The usual crew consists of four men; the test car driver, an assistant, a water truck driver and a flagman. The four man crew is sufficient for most roads,

but an additional flagman is desirable on highly congested routes.

After a location is selected on a particular road, the test car and flagman stop at a point 400 to 500 feet in advance of the test section and the flagman halts all traffic approaching from the rear. The water truck and test assistant proceed ahead to the test site and begin wetting without interfering with oncoming traffic. The test assistant controls the water from the truck. When a sufficient strip (200' to 300') is thoroughly wetted the assistant remains at the site and the water truck driver pulls the truck several hundred feet ahead, dismounts and stops oncoming traffic. The two skids are then run in quick succession, with the assistant and flagman raising and lowering the fifth-wheel as necessary, as it is not possible to back the car with this wheel down. It is generally possible to run both skids in less than two minutes after completion of wetting thus keeping the effects of evaporation and runoff to a minimum. The speed to the nearest 0.25 mph. and distance to the nearest 0.25 foot are read from the stopmeter dials and recorded by the driver after each skid.

THE PRESENT PROGRAM OF TESTING

The skid project in Indiana developed along several lines. Two hundred thirty-three roads were tested during the summer of 1954. The roads tested were selected as a sample of the state highways in every part of Indiana and included roads of various surface types, different volumes of traffic, and various ages. The data obtained during this program have been analyzed and the results are indicated later in this paper.

Indiana also has several experimental pavements and on some of these periodic skid tests are continuing. An annual skid test is performed on a surface containing silica sand to determine the long-term skid characteristics of this surface type. Semi-annual skid tests, one in the summer and the other in the winter, are also conducted on the US 31 Test Road. A section of this road near Columbus, Indiana, is constructed for a long-term comparison of the characteristics of Portland Cement Concrete and Bituminous Concrete. One of the characteristics being compared is that of skid resistance.

Another use of the skid equipment is in evaluating reported "slick" sections of highway. As the state police or highway department receives complaints of "slick" highways, the location is referred to Purdue and a skid test is scheduled for the reported location. A confirmation of the hazard by the test initiates activity by the responsible agency to eliminate the hazard.

DISCUSSION OF RESULTS FROM STATEWIDE STUDY

Four major construction types were investigated: Rock Asphalt, Portland Cement Concrete, Bituminous Concrete and other Bituminous Surfaces. A total of 233 different roads were tested in a wet condition, and 20 in the dry condition. Each road was tested at three locations, and two skids were taken at each location. All tests were made at a brake-application speed of 30 mph. All distances indicated in this report are average stopping distances from the instant of brake application and were obtained using the same skid vehicle.

For each selected location, any difference in the two skid distances gives rise to a variation which is called the skid-to-skid variance.

The three selected locations for a particular road always have somewhat different mean skid distances, and thus there is also a variation that arises from these differences. The measure of this variation is called the location-to-location variance.

Whenever more than one road has been selected in a given type or subtype, differences among the observed road means give rise to a third variance, the road-to-road variability.

Skid-to-skid variances are generally the smallest of the three types of variability since the two skids taken at the same location represent tests under the most similar conditions. The location-to-location variances represent differences that arise from variation in the surface properties of a particular road, from place to place, probably due to such factors as construction differences, varying traffic, and bleeding. Road-to-road variances, within a given type or subtypes, reflect differences in skid resistance that must be associated, for the most part, with discrepancies in age or wearing, materials and methods of construction, and volume and type of traffic to which the roads have been subjected.

The results of the tests for each road type are discussed in the following sections and are summarized in Table 1 and Figure 8. All means stated are for a brake-application speed of 30 mph. with the road surface in the wet condition. Significant differences are said to exist only when two-standard-error "regions of uncertainty" do not overlap. The standard errors used are based on only those roads included in the survey. The three variances, as previously discussed, are also shown in Table 1 and Figure 8.

It must also be noted that the difference in skidding distance between two roads or road types is given in this study for a speed of 30 mph. A much greater difference in distance would be obtained at higher speeds and could be a very critical element, certainly a very dangerous one.

Rock Asphalt

The rock asphalt roads tested displayed excellent skidding properties in the wet condition. The mean of 180 skids on 30 different roads at 30 mph. was 63.3 ft., a value significantly lower than that for any other major type, and only a few feet greater than the mean of the roads that were tested in the dry condition. The variability of the skid distances found on these roads was also found to be of an especially low order, the road-to-road variance being on a par with the skid-to-skid variances for many other types and sub-types.

An attempt was made by rank order correlation and graphing to find a relationship between the small amount of variation existing between these roads and traffic volume, but no such relationship appears to exist. The skidding characteristics of rock asphalt surfacing is, then, not apparently affected by traffic volume and age; surfaces 14 and 15 years old were found to have about the same mean skid distance as many of those of recent construction.

SUM VARIANCES,

(1)	(7)	(8)	(9)
CODE NO.	AD TO LOAD	STD. ERROR OF THE MEAN * (FT.)	STD. ERROR OF THE MEAN * (FT.)
1XX	23	0.24	0.43
111	25.51	0.17	0.38
121	38.17	2.98	1.78
2XX	36	0.29	1.24
211	397.39	0.50	1.97
221	446.28	0.36	1.60
3XX	45	0.39	1.53
31X	330.02	0.41	1.59
311	923.30	0.44	1.79
312	199.99	1.04	2.18
321	32.43	0.74	1.81
4XX	450	0.21	2.15
41X	508.30	0.35	1.68
411	618.22	0.51	2.97
412	353.57	0.48	1.81
42X	426.55	1.69	3.74
421	1,037.55	2.72	4.65
422	672.01	2.09	3.53
5XX	—	—	—
51X	918.46	2.36	5.05
511	116.77	3.12	2.55
512	1,942.84	3.55	10.39
52X	—	0.37	—
53X	—	1.52	—
54X	—	3.14	—

*
*
*

INDIANA ROADS

TABLE NO. 1

SUMMARY OF MEAN SKID DISTANCES, AVERAGE VARIANCES, AND STANDARD ERRORS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
CODE NO.	SURFACE TYPE	MEAN SKID DISTANCE (FEET)	NO. OF ROADS	AVERAGE VARIANCES SKID TO SKID	LOCATION TO LOCATION	ROAD TO ROAD	STD. ERROR OF THE MEAN * (FT.)	STD. ERROR OF THE MEAN * (FT.)
IXX	ROCK ASPHALT	62.56	32	1.02	11.39	34.23	0.24	0.43
111	STANDARD 30* OR 60*	62.25	30	0.84	4.98	25.51	0.17	0.38
121	9* SLICK TREATMENT	67.27	2	3.84	107.53	38.17	2.98	1.78
2XX	PORTLAND CEMENT CONCRETE	81.44	46	1.87	23.83	422.36	0.29	1.24
211	STONE COARSE AGG.	80.78	17	1.32	25.82	397.39	0.50	1.97
221	GRAVEL COARSE AGG.	81.83	29	2.06	22.67	446.28	0.36	1.60
3XX	BITUMINOUS CONCRETE	89.22	59	6.79	53.00	827.45	0.39	1.53
31X	STONE COARSE AGG.	88.78	55	6.99	55.65	830.02	0.41	1.59
311	NATURAL SAND	88.64	48	7.62	57.14	923.30	0.44	1.79
312	STONE SAND	89.80	7	2.64	45.43	199.99	1.04	2.18
321	GRAVEL C.A. - NAT. SAND	95.21	4	3.99	13.12	82.43	0.74	1.87
4XX	OTHER BITUMINOUS SURFACES	80.83	47	8.20	119.97	1,304.50	0.21	2.15
41X	NO BLEEDING	74.06	30	5.11	22.34	508.30	0.35	1.68
411	ALL GRAVEL	77.86	12	6.43	19.10	618.22	0.51	2.97
412	ALL STONE	71.50	18	4.24	24.51	353.57	0.48	1.81
42X	BLEEDING	92.77	17	13.64	292.26	1,426.55	1.69	3.74
421	ALL GRAVEL	103.44	8	23.71	355.32	1,037.55	2.72	4.65
422	ALL STONE	83.28	9	4.69	236.41	672.01	2.09	3.53
5XX	SPECIAL SURFACES	—	14	—	—	—	—	—
51X	BIT. CTD. AGG. (DENSE MIX.)	99.38	6	8.03	200.85	918.46	2.36	5.05
511	ALL GRAVEL	103.01	3	9.94	174.70	116.77	3.12	2.55
512	ALL STONE	95.76	3	6.12	226.99	1,942.84	3.55	10.39
52X	SILICA SAND	66.68	1	2.82	0.83	—	0.37	—
53X	BIT. CONC. (5 1/2% AP 5)	98.35	1	1.85	13.74	—	1.52	—
54X	BIT. CT. AGG. (US 40 - 4 ML. EAST OF BRAZIL)	150.46	1	0.24	59.30	—	3.14	—

* BASED ON ONLY THOSE ROADS INCLUDED IN SURVEY
 * REGARDING THE SELECTED ROADS OF EACH TYPE AS A RANDOM SAMPLE OF INDIANA ROADS
 *

ESTIMATED MEANS AND VARIANCES FOR THE SURVEY ROADS

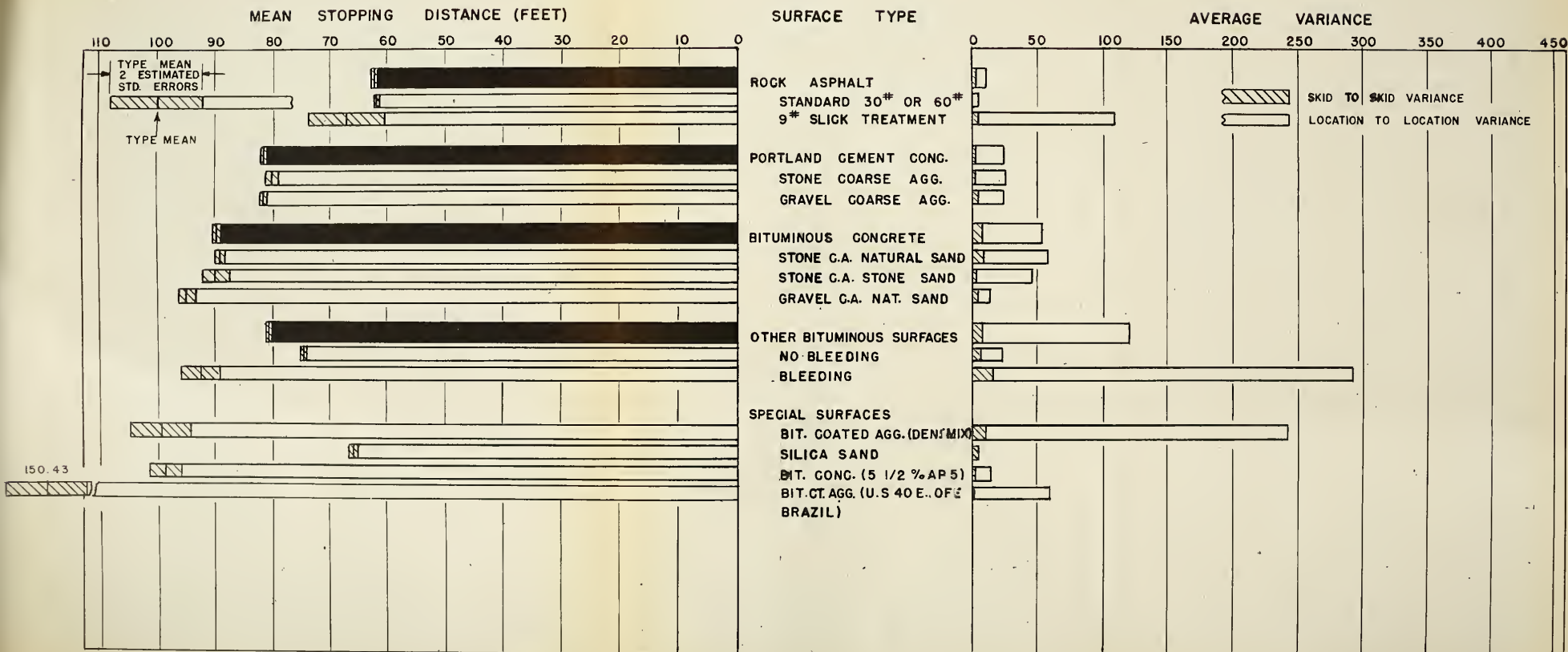


FIGURE NO. 8

Two roads that had been "de-slicked" by a thin 9 pound rock asphalt treatment were included in the survey. One of these roads was still completely covered, while a considerable portion of the resurfacing had worn off of the second. The former road displayed a mean and variance very similar to the conventional rock asphalt roads tested, while the latter had an exceedingly high mean skid distance and variance. It was concluded that the 9 pound treatment is an effective method of temporarily "de-slicking" surfaces. The type and condition of the previous surface is probably an important factor governing the service of the "de-slicking" treatments.

These tests on rock asphalt surfaces serve to substantiate the conclusions of many other experimentors that those surfaces with a harsh, gritty, sand-paper finish have superior skidding properties in the wet condition. The only other surfaces tested that had similar properties were two sections constructed with silica sand, and they, too, had excellent skidding properties and small variances.

Portland Cement Concrete

The overall mean of 276 skids run on 45 roads constructed of portland cement concrete was 81.4 feet. This value is significantly higher than that for rock asphalt, but significantly below the estimated mean for bituminous concrete.

Although the average skid-to-skid and location-to-location variance for these roads were over twice as high as those for rock asphalt, and the road-to-road variance was over 10 times as great, these variances were seldom more than half of those of the other major road types.

The comparatively small amount of variability on these roads is especially significant in view of the fact that these roads average 11.5 years considerably older and have carried more traffic than any of other major types, indicating that although the roads tested seemed to be in fairly good shape

and traffic volume, there was comparatively little variation in their skidding properties. An attempt was made to correlate the mean skid distances of all the tested roads with average traffic volume, age, and total traffic but no significant relationships appeared to exist. The roads were then separated into two groups: pre 1945 and post 1945. Both of these groups were studied individually for a relationship between mean skid distance and both average volume and total traffic volume (the product of age and daily traffic). The pre 1945 group indicated that there is no relationship between skid resistance and traffic for these older roads and thus their variability must arise from other factors not included in this investigation. The post 1945 surfaces indicate a definite increase in mean skid distance with increases in both average daily traffic and total traffic. Another conclusion indicated by this study is that traffic tends to decrease the skid resistance of portland cement concrete surfaces to a measurable degree for a few years after construction until they reach a point beyond which "polishing" action is greatly retarded. This premise was further substantiated by the fact that the post 1945 roads tested yielded a mean skid distance approximately 5 feet shorter than that for the older roads.

The portland cement concrete roads tested in the survey were also divided according to the type of coarse aggregate (gravel or stone) used in the mix, but no overall differences in either means or variances were indicated between the two types.

Bituminous Concrete

The mean skid distance found for the 59 bituminous concrete roads tested was 89.2 feet at 30 mph. This mean is significantly greater than that for those roads tested in any other major type. These surfaces were also quite variable, yielding variances almost twice those for portland cement concrete for each of the three sources of variation.

The bituminous concrete roads were divided into three major groups for comparison purposes: those constructed with stone coarse aggregate and stone sand, those with stone coarse aggregate and natural sand, and those constructed with gravel coarse aggregate and natural sand. Contrasts among these groups indicate that, for the roads tested, the roads containing stone coarse aggregate have a significantly lower mean skid distance than those constructed with gravel. Another contrast indicated that there was no significant difference between the roads constructed with natural sand and those containing stone sand. It is interesting to note that although the gravel coarse aggregate roads had the highest mean skid distance among the 3 sub-types studied here, the location-to-location and road-to-road variance is of an exceptionally low order, revealing consistency among these surfaces. It should also be pointed out that the road-to-road variances found for the stone sand roads were also extremely small, being less than half those for portland cement concrete, again suggesting a relatively consistent type of surface.

The effects of traffic on the three types of bituminous concrete were studied separately. The stone coarse aggregate, natural-sand fine aggregate roads gave indications of increasing mean skid distance with increasing total volume. The information on the other sub-types indicated no effect due to traffic volume.

Other Bituminous Surfaces

All the bituminous surfaces tested other than rock asphalt and bituminous concrete have been produced either under the general heading of other bituminous surfaces. These bituminous surfaces represent a considerable percentage of the total highway mileage in the state.

The 55 bituminous surfaces included here yielded a comparatively low overall mean of 10.3 feet; a value which is identical to that of the portland

cement concrete roads, and significantly lower than that for the bituminous concrete surfaces tested. The variability among these roads was, however, of a large magnitude, far exceeding that of any other major type for each of the three sources of variation. Individual skids on these roads ranged from 50 to 167 feet, displaying skidding properties anywhere from excellent to very poor. These high variances make it possible for any road or location to yield an average skid resistance value that is radically different from the comparatively low indicated mean.

For initial comparison purposes, the bituminous surfaces were divided into two groups, those surfaces containing stone aggregate, and those containing gravel. Those road surfaces containing gravel were found to have a significantly higher mean than those surfaced with stone. The gravel roads also displayed a greater road-to-road variance than stone, although the site-to-site and location-to-location variances did not differ to any great extent.

The inconsistent nature of these roads stems, to some extent, from the many variables inherent in these surfaces and from the many different combinations of aggregate and bituminous material that are present. The skidding properties are also influenced by the previous construction history of any particular road.

The major cause of variability for these roads, however, appears to result from the bleeding of excess bituminous material, either from the current or previous construction. This bleeding causes "fat spots" to appear, usually along the wheel tracks, but often over the entire road. These bleeding sections made it necessary for friction to be developed primarily between the bituminous material and the tire, as the aggregate was usually wholly or partially buried. High mean skid distances and high location-to-location variances were almost invariably associated with bleeding. Several bleeding roads were found to be too hazardous to test as it was impossible to keep the test vehicle on the road for the full length of skid

In order to evaluate the effects of bleeding and to make further comparisons, these bituminous surfaces were again divided into two major groups: those that evidenced some bleeding and those that were entirely free from bleeding. Comparisons were then made both within and between the groups.

The non-bleeding surfaces, as a group, displayed a mean of 74.1 feet, a value considerably below that for any major road type other than rock asphalt. The variances, too, were of a reasonably low order, especially the average location-to-location variance which was very close to the value for portland cement concrete.

The group of bleeding surfaces, on the other hand, was found to have the relatively high mean of 92.8 feet, a figure significantly higher than that for the non-bleeding surfaces, exceeding this value by over 18 feet. The skid-to-skid variance was somewhat greater for the bleeding roads and the road-to-road variance almost 3 times as great, but a rather spectacular contrast was found in the location-to-location variances. The location-to-location variance for the bleeding surfaces was over ten times that for the non-bleeding ones. This indicates that a considerable portion of the variability and high means in these surfaces can be explained by bleeding. It may also be seen that these bituminous surfaces can have very good, consistent skidding properties if no bleeding occurs.

Comparisons among aggregate types, stone, and bituminous materials were made within each of the two groups. The gravel roads were found to have a significantly higher mean within both the bleeding and non-bleeding groups, although the difference was much more pronounced for the bleeding group. This contrast further indicates that stone has better initial skidding properties even if no bleeding occurs. The variances within both groups were quite homogenous, and neither aggregate appears to give more consistent surface than the other.

Contrasts among the three prevalent sizes of aggregate in each group did not reveal any notable or significant differences in means or variances from size to size for either gravel or stone. Thus, for these roads, aggregate size does not appear to affect the skid distance to any measurable degree.

Special Sites

Several surfaces were tested during the summer program that do not strictly fall into any of the previously discussed classes, and, therefore, merit individual consideration.

The first of these is a silica sand surface on U.S. 46 east of Greensburg. This road has an appearance and texture very similar to that of rock asphalt. The mean skid distance on this section was 66.7 feet, which was significantly lower than any road type except rock asphalt. The variability, especially that from location-to-location, is of an especially low value, indicating consistency similar to rock asphalt.

A group of six bituminous coated aggregate surfaces was also included in the survey. These are designated as "dense mix" and had a plant mix surface composed of #14 sand, #11 gravel or stone aggregate combined with either RC 5 or AE 90. The overall mean of these six roads was a comparatively high 99.4 feet and both the site-to-site and location-to-location variances were quite high. This mean was significantly higher than that for any of the major road types tested.

One surface tested clearly illustrated the seriousness of skidding due to polishing of aggregate. On a section of U.S. 40 near

Brazil a bituminous coated aggregate surface has been exposed to heavy traffic throughout its entire life. No bleeding was evident on the road and much of the seal had worn off leaving a very coarse looking "open" surface. The mean skid distance on this road was 150.5 feet--the highest of any road tested in the survey. Close observation revealed each stone to be rounded and highly polished. Comparatively low variances on this road indicate this road was consistently slick from place to place.

CONCLUSIONS

The conclusions of this study are:

1. The vehicle stopping-distance method that utilizes an electrically controlled vacuum braking system and an integrated fifth wheel speedometer and odometer produces consistent and reproducible results.
2. The vehicle stopping-distance method is economical, rapid, and relatively safe at 30 mph.
3. Of all surfaces tested, rock asphalt has the best skid characteristics when wet, both as to average distance and variability.
4. A thin application of rock asphalt is a good but temporary method of de-slicking a pavement.
5. Portland Cement Concrete surfaces provide relatively good skid characteristics but are subject to polishing by traffic during the first few years of their life.
6. Bituminous Concrete surfaces, as constructed in Indiana under present specifications, do not have as good skid characteristics as Rock Asphalt or Portland Cement Concrete.
7. Bituminous Surfaces other than Rock Asphalt and Bituminous Concrete have a relatively low average skid distance but are very variable.
8. Bleeding on Bituminous surfaces results in a significant increase in the stopping distance.

9. Bituminous surfaces constructed with Indiana limestone aggregate exhibited better skidding characteristics than those constructed with Indiana gravel aggregate.
10. Bituminous surfaces that were coarse and open exhibited poor skidding characteristics.
11. Although it cannot be considered conclusive because of the small number of roads tested, surfaces constructed with Silica Sand gave good results, comparable to Rock Asphalt.
12. Since bituminous surfaces exhibited skidding distances when wet ranging from 50 to 167 feet, excellent to very poor, it is apparent that they can be designed and constructed so as to give excellent skidding characteristics.

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